

Adjustable Shock Test Sled for Haversine Pulses at 250 fps

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A new shock test sled has been developed to simulate shocks up to 2250 g peak amplitude and up to 250 ft/sec velocity change. The sled is adjustable to provide haversine shaped shock pulses with durations ranging from 4 milliseconds to 15 milliseconds utilizing a variable stack of phenolic and felt programmer material, and it allows for rapid change-over from one desired shock pulse to another. Finite element analysis was used to iterate on parameters for the programmer element to ensure success with the first hardware and to analyze a critical clamping element.

Introduction

New test requirements were developed by Sandia National Laboratory to simulate a regime of shock testing not previously performed at the Kansas City Plant operated by Honeywell Federal Manufacturing & Technologies. These environments were unique in that they involved amplitude of shock >1000g with relatively long pulse durations (greater 5 ms but less than 10 ms) and involved velocity changes up to 235 ft/sec. Ten months were available to develop, design, manufacture and prove-in this new capability.

We designed a new shock sled to deliver this new family of shock environments in a laboratory test. The performance range of the new sled includes five specific shocks (1000 g – 8 ms, 1300 - 6 ms, 1500 g – 5.4 ms, 1950 g – 6 ms, 2250 g – 5.4 ms; all haversine shaped), and it also incorporates adjustability to accommodate new shocks within this range. These shock environments result in velocity changes ranging from 160 fps to 250 fps. The test sled accommodates test articles weighing up to 20 lbs and measuring up to 10” along any axis.

Background

Most mechanical shock testing at the Kansas City Plant (KCP) is performed by attaching the unit under test to a sliding specimen carriage. This carriage is accelerated to some desired velocity by gravity or bungee cords before it impacts an elastic “programmer” element and bounces. The initial velocity of the carriage and the stiffness of the programmer control the shape, amplitude, and duration of the shock event that is imparted during impact. At the KCP, we do not have impact machines capable of generating more than 140 ft/sec of velocity change through gravity or bungee mechanisms. For tests at higher velocities, the unit under test is attached to a specimen carriage, but it is initially at rest. An elastic programmer is placed between the specimen carriage and an impact mass. The impact mass is accelerated to the desired velocity by an 18” diameter pneumatic linear actuator. The impact mass strikes the specimen carriage through the elastic programmer element and accelerates the specimen carriage generating the desired shock environment. This configuration is shown schematically in Figure 1.

In the KCP laboratory, the specimen carriage slides on rails which are attached to the impact mass to form a sled. The sled itself rides on a guide rails in front of the pneumatic actuator which provides the initial velocity. The KCP previously had the capability to perform one similar environment (1000g - 8ms haversine shock with 160 ft/sec of velocity change). Figure 2 is a photograph of the previous test sled installed on the guide rails of the South Horizontal Actuator. The actuator is visible in the upper left corner of the photograph, the impact mass is in the middle of the picture and the specimen carriage is near the bottom. The previous test sled utilized three slender rods of Delrin for the programmer, totaling 94” in length, to generate the shock pulse, and this sled was designed to produce just this one pulse. The existing Delrin rods were not capable of delivering the higher acceleration amplitudes required without fracturing.

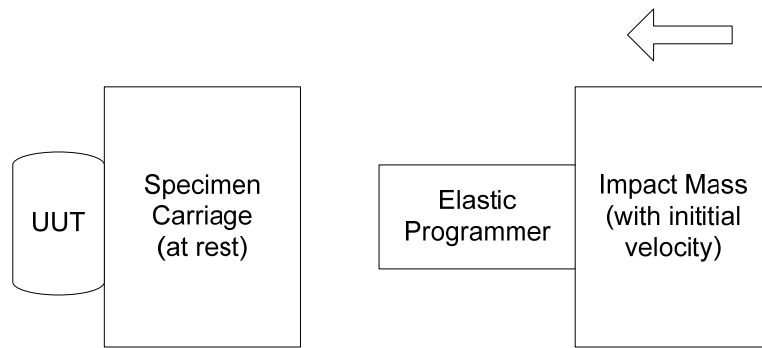


Figure 1. Schematic of Impulsive Shock Machine Configuration.

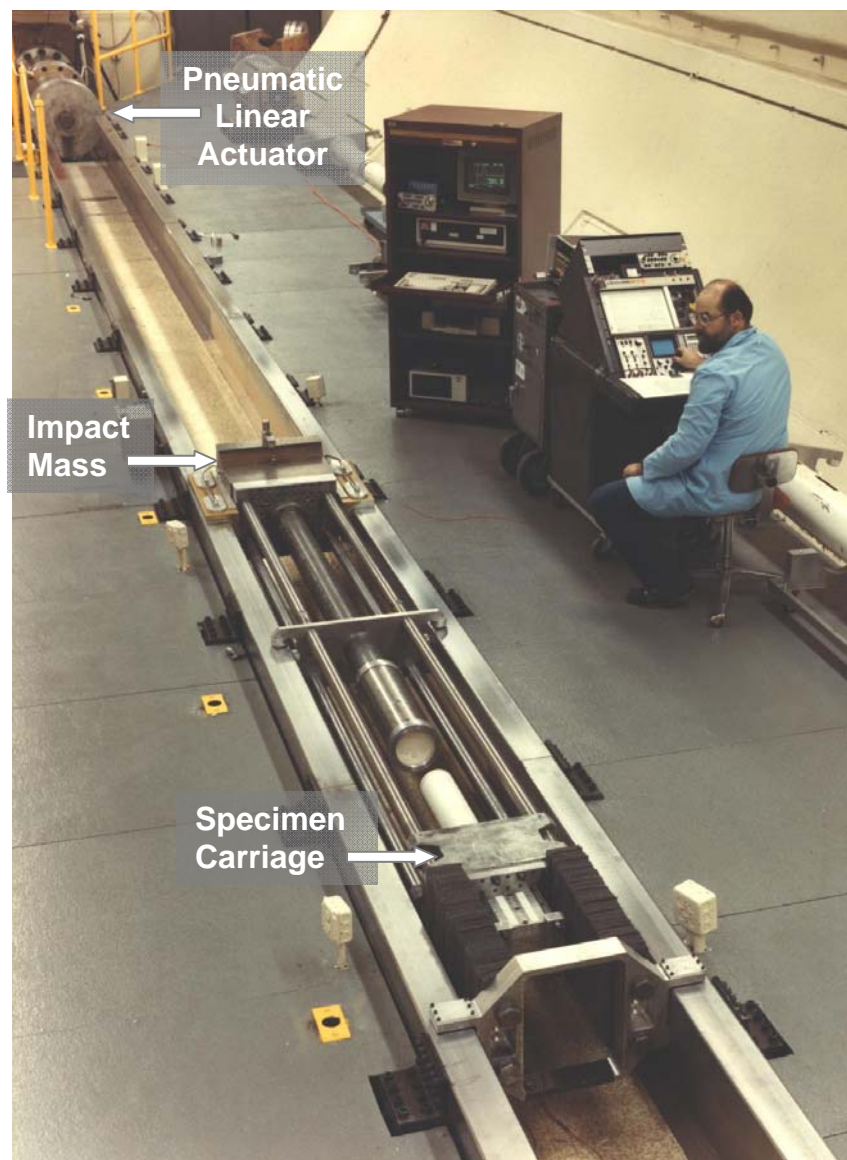


Figure 2. Previous 1000g – 8 ms sled installed in test cell

Adjustable Sled

Concept

To meet the new requirements (including schedule), a low risk approach was adopted: reuse as many conceptual elements as possible from the existing sled and evolve the design to expand the capability. It was determined to use the same basic approach of compressing an elastic element, utilizing the existing pneumatic actuator and impact mass for velocity generation, and to design the system for ease of assembly and component replacement to minimize downtime from failures.

To achieve the full range of required shocks the new sled needed to be adjustable to achieve durations from 5 milliseconds to 8 milliseconds. Due to manufacturing limitations, it is not possible to purchase Delrin rods in a large enough diameter to accommodate the higher amplitudes. Phenolic is another commonly used material for generating shock pulses. Linen filled phenolic (LE Grade) has a modulus of elasticity similar to Delrin but an ultimate strength two to three times higher in the direction perpendicular the linen lamination layers. This allows a programmer to be constructed with a similar diameter to the Delrin programmers but with much higher peak amplitude capability. In phenolic rods, the layers are parallel to the axis of the rod, and therefore the rod's strength in compression is well below the properties perpendicular to sheet stock. A new conceptual design was developed to accommodate phenolic sheets. Adjustability is achieved by creating the programmer element with a stack of discs made from 2" sheet stock. The duration of the shock is controlled by varying the number of discs in a stack. The long stacks are restrained from buckling with a containment tube enclosing them. To accommodate varying lengths of stacks, the containment tube is composed of two concentric tubes which telescope to adjust the total length. The telescoping tubes are secured in place using a quick release collar described in detail below. Reference Figure 3 and the Operation section below for a graphical explanation.

Operation

In operation, the impact mass (Figure 3, Item 3) is quickly accelerated to some initial velocity using the 18" pneumatic linear actuator. The specimen carriage (Item 4) is initially at rest and slides freely on guide rails (5). As the brake carriage (3) approaches the specimen carriage (4) the metal punch (6) enters the containment tube and impacts the stack of phenolic disks (1) and felt (9). As the stack is compressed, the specimen carriage is accelerated. This acceleration is the desired output of the test apparatus. By adjusting the initial velocity of the brake carriage (3) and the length of the stack of phenolic and felt (1 & 9) the characteristics of the acceleration pulse (i.e. shock pulse) can be controlled or "programmed". The outer containment tube slides (7) over the inner containment tube (8) to change the total length of the containment tube and therefore the length of the stack of phenolic disks that can be contained within. Spacer tubes (10) are used inside the larger diameter outer containment tube (7) to match the inside diameter of the Inner Containment Tube (8) and keep the discs aligned. The quick release collar (2) is easily removed and installed, and it joins the two tubes with a rigid connection.

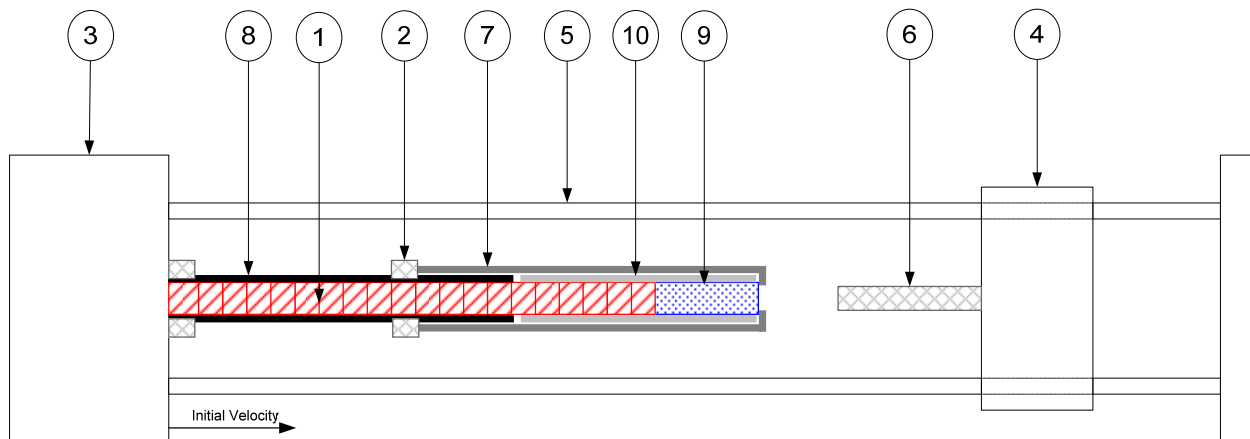


Figure 3. Schematic of Adjustable Sled

Figure 4 is an isometric view of a solid model of the full sled. The entire process of configuring the instrumentation, the sled, and the pneumatic actuator for a test takes approximately 30 minutes. Up to 12 tests can be performed in an 8 hour shift.

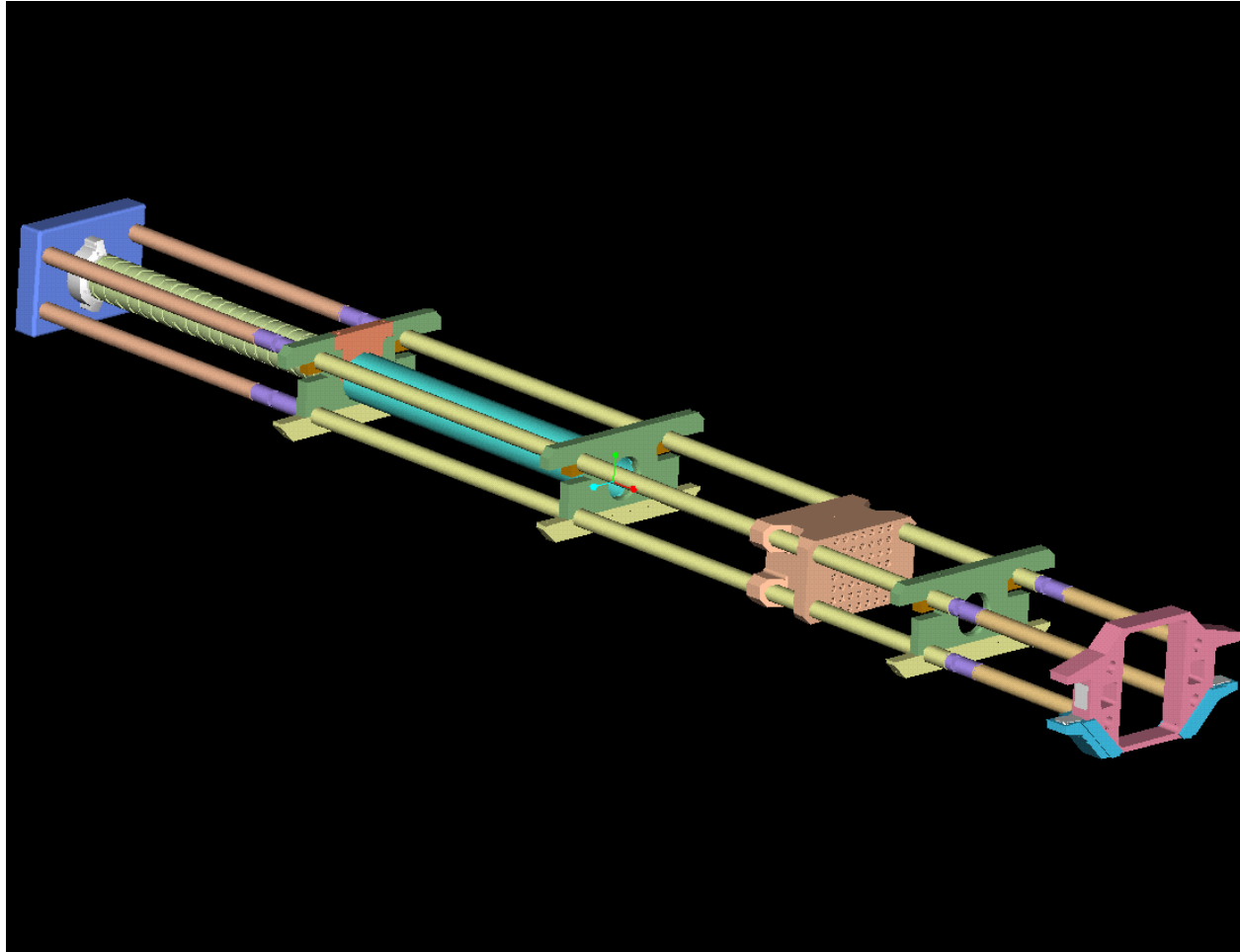


Figure 4. Solid model of final design for adjustable Sled.

Variable Length Programmer

The length of the programmer stack in combination with the initial velocity of the impact mass controls the duration, amplitude, and shape of the shock pulse. The stack of phenolic discs is held together with a bungee cord threaded through a center hole in the discs and secured at each end with a compression collar. The bungee is pre-tensioned when the stack is assembled so that there is certainty that the discs are in a solid stack prior to the impact. In addition, the bungee cord allows the assembled stack to be removed and inserted as a whole. Given that there are currently only four discrete shock requirements, the optimal programmer length can be predetermined and a preset stack of programmers can be set aside for each shock requirement. As parts are received for testing, it takes less than an hour to reconfigure the sled from one shock requirement to another.

Adjustable Containment Tube

Concept

The Inner Tube (Figure 3, Item 8) transmits large forces into the Outer Tube (Item 7) during the acceleration of the impact mass and the shock event, and these forces were estimated to determine criteria for the connector design. A tongue and groove design for the collar was created with grooves in the Inner Tube (8) and a tongue in the collar (2)

that would fit in the groove. This design is shown in cross section in Figure 5. This connection needs to be rigid during the shock event in both directions along the axis so a chamfered tongue was designed to positively wedge the connection in the axial direction. The containment tube was grooved in 2 inch increments along its length to allow for a programmer from 53 inches to 93 inches in length.

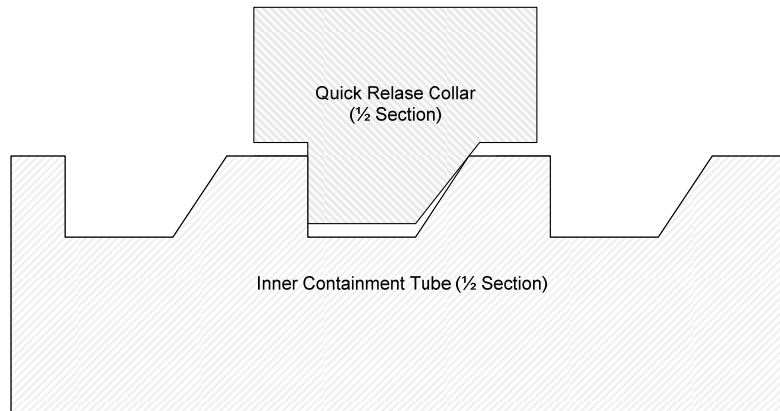


Figure 5. Schematic of Collar and Inner Containment Tube (1/2 cross section)

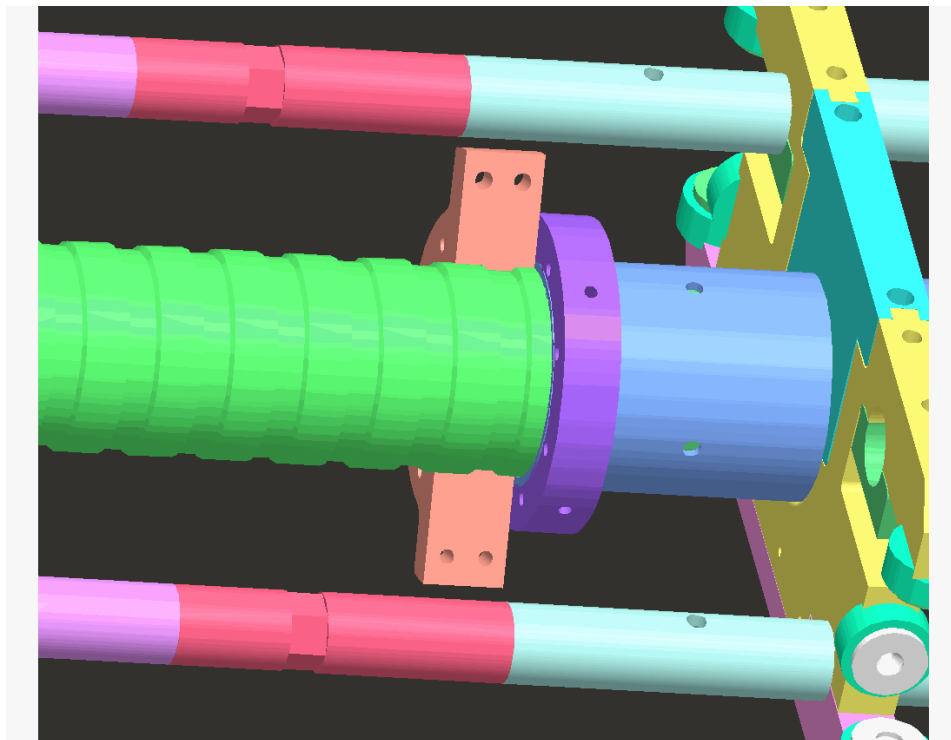


Figure 6. Solid Model of 1/2 of the Collar and Containment Tube

Contact Stress Analysis

A detailed analysis of the collar design dimensions was performed to ensure that even in maximum material condition (MMC) and least material conditions (LMC) (given reasonable manufacturing tolerances) that the tongue would lock in the groove.

A finite element analysis of this connection was also performed at LMC and MMC to ensure that the metal would not yield or change performance after repeated assembly and disassembly. Initial analysis results are shown

graphically in Figures 7 and 8; in this initial case, clamping the collar would have yielded the material under the corner. The design was optimized to develop even clamping force around the perimeter of the inner tube without yielding material at any point. In practice, the collar has been assembled and disassembled repeatedly, and it bears no indications of deformation. In addition, after repeated firings, there are no witness marks indicative of slipping at the joint.

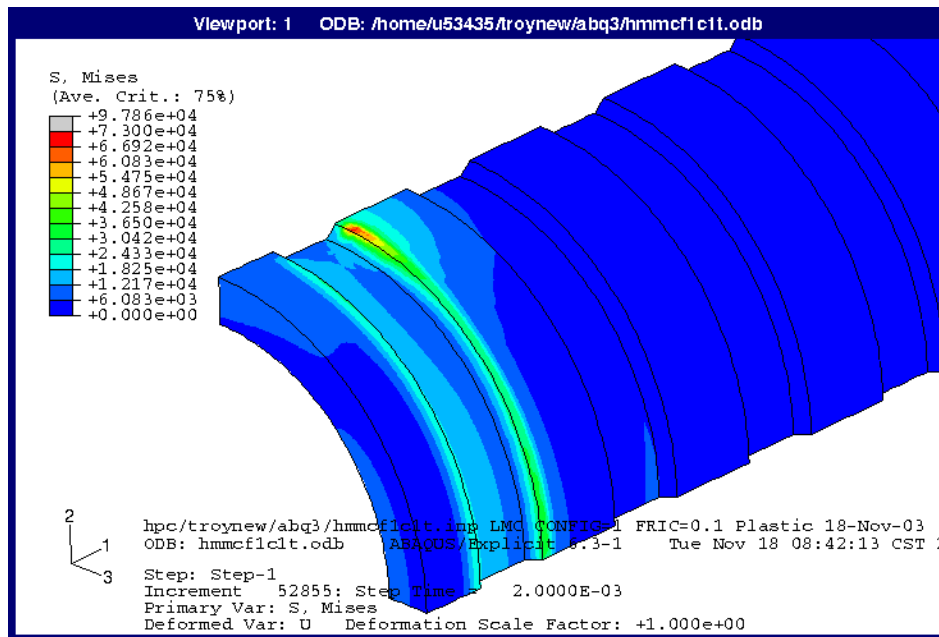


Figure 7. FEA model of 1/4 of Inner Containment Tube

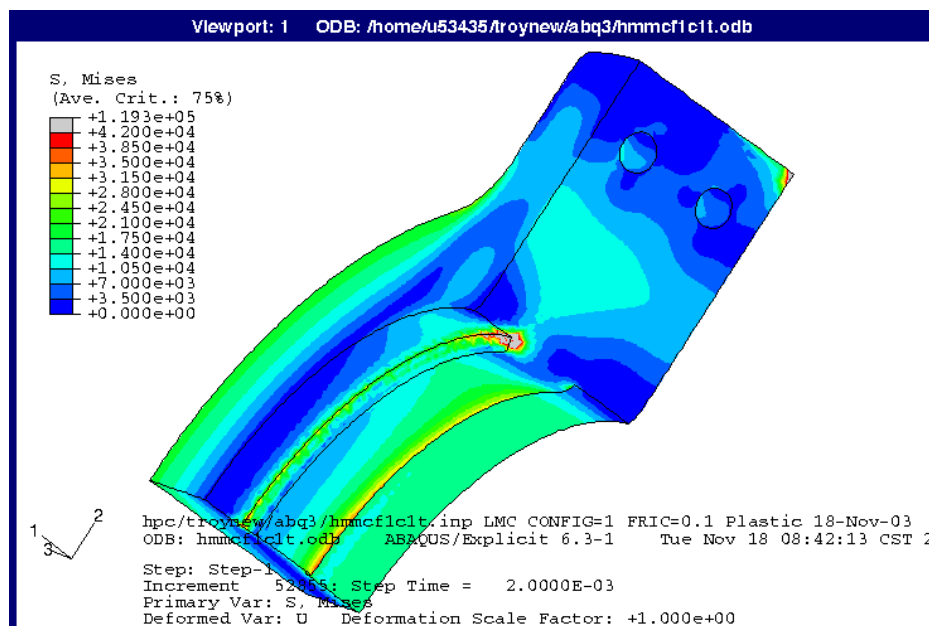


Figure 8. FEA model of 1/4 of Quick Release Collar

Programmer Length Selection

The nature of the design commits to a limited range of programmer lengths. Given the long lead time for machining the containment tube and the schedule deadline, it was important that the sled perform as intended in the first test series; there was limited time for rework and insufficient time to fabricate a new containment tube. Finite element analysis of a limited section of the sled with a detailed model of the programmer was used to gain confidence in the design. Reference Hartwig [1] for a detailed description of the finite element analysis techniques employed.

Felt Properties

A critical element in the performance of the programmer is the use of non-woven wool felt to soften the initial impact on the programmer and produce the desired haversine pulse shape. Felt exhibits a non-linear compression modulus, and it was modeled with ABAQUS® Hyperfoam material model. A series of static and dynamic tests were performed to tune the model to the material properties of the felt used in this application.

Rapid FEA analysis

Adjustments to the design of the sled required repeated models to be run to validate changes. To facilitate this iterative process and to reduce dependence on analyst availability, a web based interface for the FEA model parameters was developed. This interface allows a non-analyst, with no experience in ABAQUS, to input model parameters (diameters, lengths, modulus, and density), submit a job to the supercomputer, and have key output results posted to an accessible folder where effects could be evaluated. This efficient process allowed the design to be iterated very quickly to gain confidence that the sled design would provide the adjustability needed to cover the full range of required shock pulses. Figure 9 is a screen shot of the web interface for parameter inputs.

The screenshot shows a web browser window titled "ADVISOR Submit - Microsoft Internet Explorer provided by Honeywell FM&T". The address bar shows "http://southpark/advisor/kinSled/submit.htm". The page features a header with the "SIMULATION ADVISOR" logo and "Honeywell Federal Manufacturing and Technologies". Below the header, there are navigation links: "AESAs", "ADVISOR HOME", "RESULTS", and "CONTACT US". The main section is titled "KINEMATIC SLED" and "Enter Parameters:". It includes a "User ID:" dropdown menu with "u60346" selected. The parameters are organized into two columns. The left column contains input fields for lengths (Len1 to Len5) and density (Dens1 to Dens5), each with a range in parentheses. The right column contains input fields for modulus (E1 to E5) and a "Felt" field. Below these, there are input fields for "aluminum" and "Specimen Acceleration". A diagram on the right side of the page shows a vertical stack of five colored blocks (purple, blue, green, yellow, red) labeled "Dens1" through "Dens5" and "E1" through "E5". Below these blocks are labels for "Felt" and "aluminum". A vertical arrow on the left indicates "Velocity = 100 fps" and a horizontal arrow on the right indicates "4.30\"". The diagram is labeled "Not to Scale" and "Specimen Acceleration".

Figure 9. Simulation Advisor, web based interface to submit ABAQUS jobs

Propagating Shock Waves

FEA graphically demonstrated shock waves propagating along the length of the programmer stack. The FEA model revealed that the shock wave dramatically affects the shape of the acceleration pulse imparted to the test article, and the shock wave effects could be mitigated through the use of additional felt. The model also demonstrated that excessive felt would result in unacceptable asymmetry and distortion of the desired pulse shape. The use of the FEA model allowed these effects to be explored before the design was committed for manufacturing.

Accomplishments

This novel shock equipment consists of a sliding specimen carriage contained in a moving sled that is propelled by a pneumatic actuator. This shock equipment is performing as expected, and is capable of delivering a peak acceleration of 2250 g and durations ranging from 4 milliseconds to 15 milliseconds for test articles up to 20 lbs. Figure 10 is a plot comparing measured data from one of the first shock tests performed with the FEA prediction for that configuration, a 1300g – 6 millisecond shock pulse.

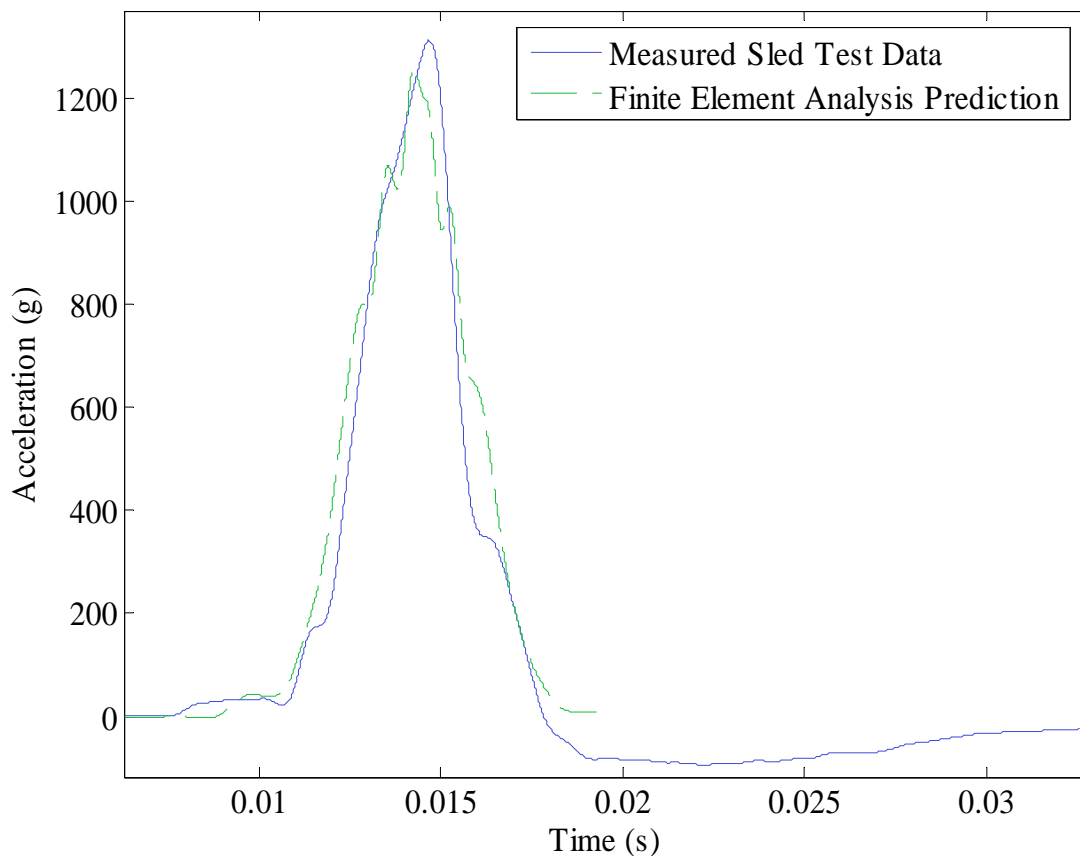


Figure 10. FEA to Measurement Correlation (1000 Hz filter applied to both)

The Kansas City Plant now has the capability to deliver a range of shock levels and durations to meet the environmental testing specifications using this shock test equipment. In addition, the shock sled is modular and thus easier to maintain than those in the past. It is able to perform tests over a broader range of shock levels and shock pulse durations than is achievable using other existing shock sleds.

Future Work

A full characterization of the sled at the margins of its performance envelope will give us a better appreciation for the range of the capabilities of the sled. There is also the possibility to explore the use of alternate materials for the programmer to expand the capability into shorter durations (fiberglass filled phenolic) or longer durations (nylon filled phenolic or Novolac resin epoxy) without substantially changing the geometry of the sled itself. Finally, there is still some opportunity to improve the shape of the shock pulse by reducing dependence on felt for shock wave mitigation, possibly through a stack of varying impedance programmers or through the use of high impedance boundaries within the programmer stack to reflect and disperse traveling shock waves.

References

[1] Hartwig, T., Hower, B., and Seaholm, A., " Using ABAQUS and Customized Simulation Advisor to Model High Impact Test Sled," Proceedings, 2004 Abaqus Users Conference. ABAQUS Users Conference, June 2004, pp 303-317.